UK CHAPTER OF THE COUNCIL OF LOGISTICS ENGINEERING PROFESSIONALS

UK CLEP ADVICE TO JACOBS STUDY ON SUPPORT MODELLING SOFTWARE

The Jacobs Study requested UK CLEP advice on 9 specific aspects of Support Modelling and Analysis (SM&A) software tools.

To be even-handed and impartial with our professional advice, it is important that we clearly state our current membership's span of expertise and where, while we have opinions, we do not have detailed expertise. For example, we do not have deep knowledge of AI and Machine Learning (ML) techniques although we can offer some relevant perspectives. It is also important that, where we have differing opinions, we express the choices clearly and present the various reasoning fairly.

To avoid commercial proprietary difficulties, we have focused on defining the requirements and rationale rather than the capabilities of specific tools. Some functions will be essential, many ideal needs, but not all will be deliverable by all potential suppliers.

To best inform the study, we wish to explain from our specialist perspective What, Why and When SM&A should be performed. This provides the background rationale for our advice, from both users and suppliers, of what the modelling software should Do. From this, we offer some opinions on How, Where and Who.

The SM&A Framework provided a roadmap for how MOD should restore its use of modelling & analysis in Support decision making. Where we feel that MOD should go further or faster than current practice, we have made comment recognising that our advice may have implications for MOD policy and implementation.

While we have addressed the 9 specific questions, we have added general commentary and suggestions on other related topics that we feel must be considered as background context.

Our advice is intended to set the ideal headmark for SM&A techniques and the required tools to enable the best possible capability for MOD to deliver its needs. In this way, we will discharge UK CLEP's objectives to use our community as unbiased Support experts for 2-way communication and to help:

REBUILD THE SUPPORT PROFESSION, IMPROVE DEFENCE OUTPUTS and **DELIVER SUPPORT ADVANTAGE**

SM&A CAPABILITY PRINCIPLES

Evidence-based Support Decisions. SM&A is essential to provide evidence on which to base Support decisions. Early in the life cycle, modelling will provide projections to inform quantitative targets that should be achievable and affordable. They should be the core of Support Requirement. Initially, targets will be uncertain estimates. Later as designs solidify, Support plans emerge and uncertainty diminishes, the maturing estimates should be yardsticks by which to judge the acceptability of the overall solution. This evolution should be a fundamental element of a mandatory Support Case maintained through-life.

Three Stages of IPS. Each of the 3 stages of IPS has a different focus which affects the SM&A needs.

- ***Design For Support*** is the phase prior to Design Freeze; during this phase, Product Support Analysis (PSA) aims to exert maximum Supportability influence on the design to maximise availability and minimise cost. The principal PSA/LSA standards (MIL-STD-1388-1A, SAE TA-STD-0017A, DEFSTAN 00-60, Def Aust 5962 & S3000L) all require SM&A to address all Support aspects of people, skills, training, parts, Support equipment, facilities, energy, information systems among others.

  In this phase sometimes usefully described as Front-End Analysis, SM&A is similar and an essential partner to operational analysis that underpins capability decisions. The SM&A should evaluate design, configuration and component choices against cost and availability baselines and assess sensitivity of the results. The SM&A results must be considered at all Design Reviews.

- ***Design The Support*** should commence after Design Freeze to shift the focus from concepts to Support plans.

  The aim of this phase is to define in detail the Support package and contract arrangements, negotiate their provision and conduct model-based Test & Evaluation (T&E) of Support prior to contract award. The T&E should provide evidence for inclusion within the mandatory Support Case that the required usage and availability outputs will be sustained affordably.

  The SM&A activity is usually referred to as Logistic Support Analysis (LSA) although the techniques and tools are almost identical to PSA. Multiple techniques are required but they must be coherent:

  - Reliability Centred Maintenance (RCM) based on Failure Mode Effects & Criticality Analysis (FMECA) of the design. RCM sets the optimum safe and cost-effective maintenance policies for the system and components including how activities are packaged into maintenance plans.
  - Level / Location of Repair Analysis (LORA) sets the optimum maintenance and repair policies and locations which may be different for systems in different operating locations depending on shipping routes and turnround times. LORA Standards are evolving towards Level / Location of Repair & Maintenance Analysis[1].
  - Resource analysis and optimisation must be conducted simultaneously across all logistic types including inventory, personnel, support equipment, facilities, etc.

    Optimisation using annually averaged, long-term, steady-state assumptions will generate incorrect solutions as will modelling just inventory. Changes in critical parameters over time such as fleet size, locations and usage as well as reliability, price and lead times must be modelled. Alternative modelling approaches are discussed in Annex B.

    Optimisation is usually to maximise availability against cost. This is logical to calculate global stock against capital or annual budgets. However, cost is not the most useful basis to optimise deployment spares where either weight for air transport or packed volume may be more appropriate. Likewise, part-packed volume may be more relevant for optimised stocks onboard submarines. Optimisation tools must optimise against bases other than cost.

    Economic optimisation produces 'knife edge' solutions that must be balanced by measures to enhance resilience and endure under Contested Logistics. These are best evaluated through several techniques including discrete event simulation[2].
  - Throughout the system life cycle, cost estimation is critical. It must reflect the varying frequency, costs and duration of: system usage in each role, location and operational scenario; preventative, corrective and condition-based monitoring maintenance; system upgrades that require maintenance activity; administrative & logistic delay times for parts, people, support equipment and facilities, information; training programs; and resources. This implies a bottom-up, activity-based approach rather than top-down simplification that will erode and ultimately ignore real-world granularity.

    Life cycle and annual operating and support (O&S) costs may be needed in different cost breakdown structures and formats such as: capital v operating: by budget holders; by system, sub-system etc; by supplier; etc. Costing tools must be able to present different views of the same costs without recalculation.

    Multiple alternative operational scenarios may be envisaged or emerge. Alternative Support arrangements including maintenance and repair policies, locations, resupply times and costs may be employed but will take time to implement. Discrete event simulation is best suited to evaluate the effectiveness on specified systems of predetermined Support packages and resilience reserves.

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1 LORA is being updated in the forthcoming global AS1390 standard.

2 System Dynamics simulation is not possible as the many individual causal loops are too numerous and complex to be measured and metricated. Agent-based modelling can be useful if also using discrete event techniques.

- ***Support The Design*** activity should monitor, identify and resolve any Support issues, and seek Continuous Improvement after the system enters service. Regular feedback of reliable in-service data is essential as the real world will always be different from projections.

  SM&A must compare field data against the availability Requirements and create the Baseline Comparative System to evaluate proposed improvements. SM&A must also evaluate the efficacy and cost-effectiveness of proposed improvements either to the Support package, maintenance policies, the system design or system usage. In extremis, the costs for limited benefits can justify living with shortfalls.

  Structured root cause analysis of in-service Support performance must be enabled by SM&A during this phase to evaluate potential remedies including their effect, cost and timeliness.

  All the techniques and tools listed above may be needed to identify shortfalls and evaluate remedies or improvements. Because of the considerable and inevitable variety, SM&A should use discrete event simulation with standard Business Intelligence tools such as MS PowerBI to provide additional post-modelling processing and focused visualisation of results.

Data Management. Trustworthy data is critical to robust SM&A. MOD should create, capture, own, manage, assure data quality, and maintain data currency through-life within a central data store as the only approved source of data for SM&A. This approach will maximise reuse across systems. While the S-Series is still not fully mature, and some of the process elements in SX000i are not yet clear, the SM&A modelling environment must be defined. The data formats should comply with the AIA/ASD S-Series specifications. The data field relationships within the SM&A database should be defined openly to meet all expected SM&A needs. The data source could be an LSAR noting that many have different standards. Interfaces will be needed to a separate modelling database to avoid corrupting master data with 'What If' alternatives. Interfaces will also be needed to connect with a range of ERP and other information systems.

The data required for SM&A is in 3 areas. The operational scenario and required usage are set by the end user. The Design Authority provides data for Maintenance and Logistically Significant Items (MSIs & LSIs) within the equipment breakdown structure together with their associated RM&T characteristics. PSA/LSA defines the Support needs which must be contracted by the customer.

The scope and size of the specific data needed for SM&A is relatively small compared with a typical LSAR. Most, perhaps 85%, is Static such as the equipment breakdown structure which does not change unless the design changes. The remaining 15% is Dynamic such as item reliability, turnround times and prices which will change frequently over time. Real-world feedback from in-service work, asset and inventory management systems must be used to update initial assumptions.

Data quality should be assessed to inform confidence in SM&A and improvement actively managed. The central data store should have capabilities to support these needs.

Verification & Validation of Data, Tools and Models. MOD has not conducted independent Verification & Validation (V&V) of SM&A tools for many years. However, the HofC Public Accounts Committee demanded clear principles for departments to follow on the publication of models, their outputs, and registers of business-critical models. This was issued as HMT Aqua Book: guidance on producing quality analysis for government. All SM&A needs V&V of the data, tools and model construction to ensure that the SM&A meets the RIGOUR criteria within the Aqua Book[3].

Summary

SM&A is critical to enable evidence-based decision making for Support. It should start from the earliest possible stage to inform ***Design For Support*** when Support must feature in all Design Reviews, is central to ***Design The Support***, and must continue regularly to update forecasts using data fed back from in-service experience. The Support Requirements must form the core of the Support Case and monitored to identify shortfalls with SM&A used to devise remedies and evaluate Support opportunities for continuous improvement through-life.

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[3] The Aqua Book: guidance on producing quality analysis - GOV.UK (www.gov.uk)

Multiple techniques, and associated tools, are needed for the various analytical needs: Front-End Analysis and LORA; RCM-based maintenance policies; simultaneous logistics resource optimisation of people, parts, tools, support equipment, facilities and energy; life cycle and Operating & Support cost projections; simulation for valuation of options of alternative scenarios; and Business Intelligence tools for flexible reporting including visualisation And going forward, the ability to take account of and trade-off environmental factors will become increasingly important.

All SM&A activity must be supported by robust and trustworthy data. The data needed for SM&A to inform planning decisions is only a small portion of the data needed to execute Support. The critical SM&A sub-set must be captured, assessed for quality, cleansed where necessary, stored centrally and maintained through-life as the approved source for all SM&A. The data, tools and models must deliver trustworthy results which results from robust process guidance of the HMT Aqua Book.

Finally, SQEP are the critical enabler but, unfortunately, the lack of MOD focus on SM&A over the last 25 years has led to a loss of MOD's intelligent customer knowledge, expertise, capability and capacity. In response, industry has paid less attention to SM&A. This national weakness will take some time to resolve. MOD has lost its organic knowledge and is struggling to decide how to recover and rebuild the required capacity. It will probably require interim outsourcing for both training and mentoring and productive SM&A activity to capture and exploit the knowledge of the few remaining but ageing personnel.

As a fundamental part of our mission, UK CLEP stands ready to help accelerate this journey.

NEXT STEPS

This advice has been intentionally product agnostic. To take this advice forward, the next logical step would be to develop an outline functional specification of both the overall SM&A architecture and cardinal points requirements for tools to provide specific functions. That Cardinal Points Specification would be the basis for selection of specific tools based on individual commercial proposals. The coordination of the next stage could be managed by PDP on MOD's behalf who would retain ultimate responsibility.

Subject to agreeing some method of compensation for the effort, UK CLEP would be very happy to help with this work while remaining independent and tool agnostic.

Approved by the Co-Chairs of UK CLEP

Annexes:

A. Responses To 9 Specific Questions
B. Inventory Management and Optimisation
C. Level of Repair Analysis

ANNEX A - RESPONSES TO 9 SPECIFIC QUESTIONS

- **Fleet**
  - Routing & scheduling

    Scheduling maintenance is a large and complex Wicked problem - whatever you do, including doing nothing, changes the problem over time. On scale, consider a fleet of 100 aircraft each comprising 2-3000 MSI/LSIs that may require at least 500 individual maintenance activities of different tracked periodicities that need to be assembled into logical work packages taking account of work to strip for access and test.

    Each system faces different challenges arising from the complex interaction of: fleet size and usage patterns; sustainment of minimum capability levels for training and contingency operations; past and future deployments; fleets-within-fleets and desired upgrades; deferred maintenance backlogs; preventative maintenance periodicities and latitudes including for out-of-phase items; planned maintenance durations; cannibalisation opportunities; people, parts, equipment and facility capacity constraints; among others.

    Routing primarily affects the delivery of spare parts. As this is managed centrally for Defence with Standard Priority Codes defining the various permitted timescales for demands, this is not directly a SM&A issue. Direct delivery by contractor is similarly outside the scope of SM&A. Rather, the defined transportation times are inputs to the modelling.

  - Management

    Optimised packaging of work items defined by RCM and other external demands such as modification programs is more of an art form than a precise science. The fundamental tool for fleet management is a stagger chart to smooth the flow of unusable systems through maintenance programs. Each fleet will be different and, most probably, use human judgement and experience supported by significant but basic information and tools such as Excel or MS project to construct the planned program. Some might claim, perhaps correctly, that AI or use of Agent-based Modelling could in time improve scheduling and management, but we have not yet seen automated tools that are superior to human experience. Regrettably, experience suggests that both MOD and Industry are stuck with the mindset of using Excel which is often not V&V'd[4] despite clear evidence of its inferiority.

- **Inventory**

  You asked 3 questions about inventory management.

  - Optimisation of stock levels in terms of quantity held or procured direct from supplier.
  - Geographical analysis of best location to serve from.

    Note: Determining the most appropriate maintenance policy and, from that calculating the optimum repair policies and stock locations, is the purpose of LORA or, more completely, location of maintenance analysis. Inventory modelling calculates the optimum range and scale by location for the defined operating and Support scenario.

  - Multi-Indenture Multi Echelon (MIME) modelling to understand what is required to sustain a system over a period of time whilst also benchmarking requirements against a number of different scenarios.

4 BAE SYSTEMS have used V&V'd simulation models (Witness) to address end-to-end fleet and maintenance modelling. Benefits included the ability to run multiple scenarios quickly. It was developed for RSAF Typhoon, transferred with developments to UK Typhoon, and then further developed and used for Hawk at RAF Valley. The intent was that it would be used on all future Air Platforms but, for unknown reasons, the capability has been lost to be replaced by 'easy' Excel.

Availability-based MIME is the most appropriate method to optimise stock holdings at each location, typically by 25-33% more cheaply than Single Item Modelling (SIM).

Unfortunately, optimised inventory solutions using steady-state assumptions are ‘knife edge’ with small change in the scenario or underlying data affecting the cost-effectiveness. Spares packages are also procured some time before being used in other scenarios with little time to adjust stock holdings. Therefore, the package must be tested against multiple operational scenarios to determine what additional stock should be procured for risk-based resilience reserves.

We have supplemented these summary comments in more detail as set out in Annex B - Inventory Management and Optimisation. The additional key points are summarised below:

- Holding every spare part needed when and where required will never be efficient or affordable. Moreover, providing spares does not always deliver effective support since maintenance activity requires other resources such as skilled people, tools, test equipment, facilities, documentation etc. Simultaneous multi-resource optimisation is essential.
- There are many metrics of spares availability but System A_0 is the most important. Optimised inventory should deliver ***‘Happy Systems’*** not just ***‘Happy Shelves’***.
- Required spares stocks are defined by the Range and Scale by location. Spares provisioning requires both Initial Provisioning (IP) and Re-Provisioning (RP).
- There are 2 principal spares provisioning methods: SIM assesses each item in isolation and ignores its cost, whereas Availability-based system modelling (MIME) assesses all items simultaneously using its costed-weighted contribution to A_0 using Marginal Analysis Techniques. Availability-based system modelling costs are typically 50% of the cost of engineering judgement and 25-33% cheaper than Single-Item Modelling. This has been substantiated by MOD’s own analysis.
- MOD’s automated RP systems use SIM methods to respond to predicted shortfalls. This approach erodes the initial benefit of Availability-based IP leading to wasteful excess stocks. Availability-based modelling should be used for regular continuous RP through-life.

  In contrast, industry tends to use automated Kanban systems where they are contracted to meet fill rate targets as this eases the order administration burden. However, care must be taken with the interaction between PIs and the payment mechanisms which can pervert behaviour[5] to maximise overall fill rates at the expense of the important high-value repairables or P-Class spares. The most effective approach, for which current tools exist[6], is to conduct continuous availability-based RP.

- **Personnel**

  Understand the availability of suitably qualified and experienced personnel and assignment to task. There are 2 personnel-related aspects which must be addressed with SM&A: the number, skills and location of trained personnel to conduct maintenance; and the number of skilled people to undertake SM&A.

  - **Maintenance Personnel**. The availability, number and cost of sufficient trained maintenance personnel at each operating and Support location are essential elements of the Support solution. The need is driven by the work required, as calculated within LORA/LOMA, at each location. These are best calculated in a bottom-up, activity-based model which must include the training needed to cope with personnel churn. These tasks and courses all require personnel, equipment and other resources, and funding, to deliver sufficient personnel to

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5 In a historic Merlin example, Augusta-Westland were paid against an overall fill rate PI for combined P, L and C Class stores. Rather than resolve serious R&O issues with high-value repairables, they overfilled C Class bins for only £6M to meet the PI rather than procure much more expensive additional gear boxes, rotor blades, avionic LRUs etc. This approach was only revealed by detailed modelling.

6 As we are aware of only one proprietary tool, we have refrained from further comment.

sustain the active workforce. SM&A tools are required that include these demands and costs which may include simulation.

- **SM&A Personnel**. The personnel needed to conduct SM&A within MOD fall into 3 categories: data capture and quality assessment; data store management; and modelling, analysis and results presentation. Specialist skills are needed in each category; people skilled in all 3 areas are very rare. While each project could 'own' dedicated staff, this approach is likely to be either inefficient or inadequate and would require many more software licences. A specialist centralised SM&A function serving all DTs will be more efficient, skilled and experienced with higher quality standards as expertise and best practice is spread internally. In our view, the model high water mark for this capability was represented by the DLO's Logistics Analysis Research Organisation (LARO). Regrettably, LARO was disbanded to save manpower at great subsequent cost to projects and the loss of MOD's intelligent customer status. Our advice is drawn from experience of the strengths of that organisation but does not seek to replicate it.

    - Data Capture and Quality Assessment. Data capture from approved sources, quality assessment and cleansing are vital prior functions to modelling. Platform specialists, typically experienced SNCOs with practical maintenance experience on each weapon system, should have primary responsibility to collect, review, cleanse and maintain relevant data. They could manage data for more than one platform within the same class such as helicopters, submarines, AFVs etc. They would liaise closely with relevant DTs, OEMs, operating and maintenance units to understand current Support performance issues, modifications and partial fleet embodiment of variants.

      Their role would be to ensure that the central SM&A database was as accurate, complete and current as possible. They would manage master modelling data for: the equipment breakdown structure; platform and component reliability estimates; cost and price data; NATO codification of alternative parts; fleet usage by Unit and aircraft serial number including fleet size and allocation, usage hours, fatigue consumption etc; and maintain the operating scenarios for use in the modelling.

      As a yardstick, LARO employed a team of 30 SNCOs to satisfy the need across all Air DTs in an era of largely manual recording. No special skills are needed.

    - Database & Network Administrators. A small team of 2-3 people would be needed to manage and maintain the central data store and any associated used for data capture and by analysts. They would be be responsible for system and data security including back-ups. They would also load, manage and maintain standard common data such as the global ISIS parts catalogue, FEDLOG and Codification data.

    - Modelling, Analysis and Results Presentation. A team of expert modelers and BI specialists would use the approved data to build models and present results for LORA/LOMA, spares optimization and WLC for all DTs using the available tools.

      The modellers would model each fleet, each year for predicted Support performance and resilience needs against alternative operational scenarios defined by MOD ranging from normal peacetime usage through exercise and deployments up to and including full contingency and wartime operations. They could also perform ad-hoc SM&A tasks to inform strategic decisions such as changes in activity levels, modification programmes, fleet rebasing, fleet build-up and run-down plans, and potential or unpredicted operational deployments and conflicts.

      As a yardstick, LARO employed a team of 12 expert modellers to model every RAF fixed and rotary platform including all marks and sub fleets around the world. BAE Systems used to employ circa 25 people for their Air contracts.

The most important task for MOD will need a blend of experience in all 3 areas to participate in a Concept of Analysis at the launch of every project. This exercise defines the analytical need, the best approach, the tools required, what data is needed and from what sources including assumptions, what results are required and in what format, and how the modelling will be assured.

- **Whole Life Cost**
    - To include the full life cycle of a defined demand, cost per unit of inventory, spares required over a period of time, storage and movement costs etc.

      The operating and support cost of a system comprises operational and maintenance people, training, spares, support equipment, technical documentation, information systems, energy including fuel, facilities, contracted R&O, transportation, packaging storage, administration, post-design services, upgrades and others. All must be included through-life for a comprehensive cost although some are fixed standing charges, some are driven by usage while others are externally demanded events from the user.

      A comprehensive Cost Breakdown Structure (CBS) should be developed based upon a common MOD standard for Support costs but tailored to be appropriate for each project. The CBS should reflect the cost drivers and be populated to provide a baseline. The major cost drivers of people, maintenance and spares should be calculated for each usage scenario taking account of spares, people, R&O, transportation, storage and other related costs. An activity-based model should be used to generate the cost data for assembly externally. The CBS should be sufficiently flexible to allow assembly in various ways and categories usually using a Business Intelligence tool.

      That said, it should be recognised that industry will develop its own internal contract cost model for the period of its contract liabilities so as to understand profitability, cash flow and risk. This will reflect not just internal costs but also the prices that it intends to charge the customer. Unless incentivised by through-life arrangements, industry will not focus on whole-life costs but only those within the contract period. This implies that only MOD will want and be able to manage a true Through-Life cost perspective including its future wishes such as capability upgrades.

- **Supply Chain**
    - To include the reverse supply chain

      The reverse supply chain must be reflected in SM&A to capture the transportation costs, delays, and the items within the return pipeline. These are all vital inputs to determine the stock required to populate the full repair loop.

      Mechanisms are also required within SM&A tools to evaluate the effect of changing overall repair loops and the impact on spares stocks offset against the cost of accelerating transportation and repairs. Where excess stock is held, the potential savings from slower, cheaper transportation or repair holidays should be calculated.

    - Analysis to determine best ROI on repair vs replace and if repairs should be done in the field, sent back to depot, or sent back to supplier.

      This is fundamentally a LORA/LOMA issue. There are 2 stages to LORA: non-economic analysis for overriding strategic factors that determine the solution, and then economic analysis.

      LORA is a complex topic. As with Inventory Management & Optimisation, we have chosen to supplement these summary comments in more detail as set out in Annex C – Level of Repair Analysis. The key points are summarised below:

        - Front-End Analysis (FEA) and Level of Repair Analysis (LORA) are related activities to take account of support throughout the life cycle. They must be employed to establish the expected system availability, LOR policy, spares analysis and LCC.
        - FEA is conducted early in the design stages to inform equipment selection. Part and Configuration Trade-Off Analysis allows designers to evaluate configuration options and to optimise designs for LCC.
        - LORA is conducted to determine the least-cost feasible repair level or discard (scrap) option for performing maintenance actions and to drive equipment design in that direction. It is conducted to reflect maintenance policy and the capabilities of

maintenance organisations with respect to the number of maintenance levels, their diagnostic capability and the skill sets and skill levels of their staff.

- Depth (what) and Level/Location of repair (where) are important independent variables which in combination define the Repair Policy for an item.
- LORA is a combination of economic and non-economic factors. It is typically conducted for each item in isolation, but a holistic approach to share the costs of maintenance and test resource costs across multiple items is better and can be more cost effective.
- The need for frequent equipment modifications, often conducted during repair or using the same facilities and resources, must be included in Level of Repair & Change Analysis.
- Sensitivity Analysis is crucial to managing program risk and cost.
- Modelling and actively managing the reverse supply chain to reflect real-world experience must be conducted.

The correct repair policy also depends on the various failure modes which will define the extent of repair needed and the resources required. Thus, a flexible Repair Fraction mechanism based on failure modes must be incorporated.

- **Maintenance**
  - Visibility of jobs required to sustain a platform over a period of time including a breakdown of all associated costs.

    Predictive analysis on spares requirements for preventative maintenance based on manufacturer's recommended life cycles and actual failure rates is straightforward based on various usage parameters such as flying hours, miles, days, fatigue index, etc. The demand for lifed components can be forecast with high confidence. Condition-based monitoring techniques such as Inspect & Repair As Necessary (IRAN) or oil and wear analysis determine the need for future maintenance with periodicities usually set sufficiently frequently to provide safe advance warning as defined by RCM analysis. Maintenance events arising from these triggers can usually be planned to ensure that all resources are available when needed but may, in some circumstances, generate unplanned corrective maintenance.

    In contrast, corrective maintenance is usually unpredicted depending on failure characteristics also called the hazard function. Specific light bulb failures cannot be predicted whereas some mechanical failures may provide early warning such that rectification can be deferred for a period often subject to additional regular inspections. Annual averages can be calculated to ensure that sufficient stock is held but the specific arisings are inevitably random. Incorporating Variance to Mean Ratio of arising profiles in the calculations is essential.

    The detailed costs of such maintenance including all necessary logistic resources including people, support equipment and piece parts can be calculated directly either on average or, better, using an activity-based model.

  - Projection of maintenance plans for a deployed fleet

    Preventative maintenance for a deployed fleet is a straightforward problem for specified usage over a defined period. Often major maintenance will be either anticipated or deferred to avoid tasks on deployment. Where unavoidable, all the necessary logistic resources including people, parts and any special support equipment must also be deployed.

    However, every platform will have detailed differences which greatly complicate requirements for generic software tool outputs. For simple platforms, projections are usually performed satisfactorily on spreadsheets with data drawn from the Systems of Record. As complexity increases for multiple roles, configurations and platform capabilities, use of Business Intelligence tools visualisations becomes essential[7] to select suitable platforms, identify the planned activities, duration and resources, and manage the work.

[7] On RAAF F35, deployment planning visualisation uses a 2D plot of flying hours against days available with Low Observability status represented by icon size and colour. Filters are used to specify mission requirements.

- Consideration toward naval ships that require maintenance upon returning to port scheduling whilst avoiding bottlenecks

  Ship maintenance is also a Wicked problem especially since naval ships and submarines are very complex systems of systems. Sustaining continuous operations with small fleet sizes and limited, very expensive shore facilities such as dry-docks overly constrain maintenance periods. While short-duration maintenance alongside can be predicted, the necessary resources of people, parts, specialist equipment and time can all be forecast, the needs during deep refit and dry-dock maintenance can be extremely complex lasting at least many months but more often years. In practice, many ships enter refit with more work planned and emergent than can be achieved resulting in ships returning to the fleet with an ever-growing backlog.

  The situation is complicated by typical naval configuration management. Each ship, even from the same class, tends to be its own prototype which is compounded by the need to repair at sea on extended commissions. Configuration audit at the start of maintenance periods is usually essential to confirm the scope of work and this delays ordering of resources and detailed planning. Secondly, each class of vessel is managed differently using a wide range of independent equipment contracts. This contractual complexity has been shown to erode availability by up to 30%.

  There is a current program challenge to save one year of an anticipated 6-year refit period but it is not yet known how this could be achieved. Previous efforts have been made to use simulation tools such as Agent-Based modelling to improve scheduled performance but the models were extremely complex taking more than 24 hours to run but without major practical effect. At present, there is no clear software solution to this problem.

- **Facilities**
  - To include both the digital twinning of physical structures and modelling to sustain those structures.

    Facilities can be a major constraint on planned maintenance but are frequently and incorrectly considered as second-order items. This is most evident in naval maintenance especially for submarines.

    SM&A should be focused on modelling the required demand for these facilities and the impact on fleet cost and Support performance of constrained facilities and resources. Other disciplines are more suited to modelling facilities maintenance, probably using digital twins of the built environment. Facilities management is a separate specialist field. That said, Support specialists must work with facilities development teams to ensure that they meet the long-term need and the capital and running costs are correctly captured.

- **Training**

  As training is a DLOD, the cost and effectiveness of the training system must be considered in the overall whole-life cost. Its vital outcomes are sufficient trained personnel to sustain operating and maintenance personnel despite the inevitable churn, and at what cost. The outcomes can be modelled separately with the outputs used as inputs to a higher-level system model.

  - Simulations

    The training system will comprise the training environment of instructors, training equipment including simulators and other synthetic training equipment, facilities and, of course, the time spent by students to learn their skills. The training system can be modelled in the same way and using the same tools as any other system.

  - Staff Development

    Developing sufficient SQEP personnel in SM&A has been a severe problem for the last 20 years. Historically, suitable Service personnel were selected for their engineering and logistics background and trained partly by internal courses and partly though ongoing mentoring to sustain SM&A capability within LARO and its predecessors. Even then, analysts typically took 18-24 months to become fully proficient without significant supervision and mentoring.

Personnel with developed skills leaving the Services often transferred to Industry. With the disbandment of LARO and the lack of focus on SM&A, the traditional source dried to a trickle. Industry has also reduced its capacity and capabilities in response to reduced demand and effective oversight from MOD. Much of the experience, expertise and almost all the capacity in both MOD and industry has been lost.

If MOD mandates SM&A for all projects, as we believe it should be, they will not be able to build sufficient capability and capacity for some time. Demand will swamp capacity leading to inadequate SM&A quality which will be self-defeating. DE&S' modelling apprenticeship schemes are to be applauded but will take many years to have effect. This suggests 2 essential and urgent actions are required:

- **Outsourcing Training**. Since MOD does not have sufficient training capacity or expertise to train the probable numbers, they should urgently consider outsourcing SM&A training. Historically, essential background knowledge of why, what, when and how SM&A should be performed could safely be assumed but that is no longer true as fewer people have any experience, and those that do are ageing rapidly. The window to capture and transfer that knowledge and expertise to later generations is closing rapidly.

  The training must include the fundamentals of SM&A for which no courses currently exist in addition to the usual specific training in software tools. A training needs analysis is needed to capture the training objectives and define the syllabus.

- **Outsourcing SM&A Activity**. Until MOD rebuilds sufficient intelligent customer capacity, and perhaps longer, it would be appropriate for MOD to outsource SM&A activity to independent organisations subject to central peer review and quality control. The work should include mentoring of newly trained MOD staff using actual projects, develop internal peer review and assurance processes, and help to rebuild MOD's intelligent customer capability. MOD must retain ultimate responsibility and accountability for SM&A.

- **Sustainable Support**
  - Is there any functionality to run the scenarios in the previously mentioned areas but make adjustments to take environmental impact into account. Can we achieve desired levels of availability while reducing carbon emissions and what are the effects of carbon reduction on overall cost to deliver?

    Traditional SM&A has optimised availability against cost to determine the most cost-effective Support package. Environmental factors are changing that trade-off from 2 to 3-dimensions, from a classic optimal curve to a 3-D trade space.

    In future, environmental factors may have sufficient weight to affect the availability - cost balance by introducing factors such as Global Warming (GW -emissions) and Embedded Energy (EE) consumed during manufacture, use and disposal. To help this thinking and focus on components of greatest significance, a new term Environmentally Significant Item (ESI) has been devised to mirror MSI & LSI.

    Tools currently exist that allocate energy consumption such as fuel to system usage. This functionality can be applied to the manufacture, use and disposal of both systems, parts including R&O and scrappage. People, support equipment and energy sources (eg, electricity grid, Blue, Green or Turquoise Liquid Hydrogen, Lithium-Ion and other novel batteries). As GW and EE are analogous to energy, they can also be modelled using the tools without change. Existing activity-based and spares models can be supplemented with relevant data with BI used to present results as required.

    The RAF RCO commissioned Project MONET to examine how environmental considerations for light training aircraft could contribute to RAF achieving its Net Zero 40 target. The study devised the concepts set out above to apply ESIs in a quantified case study using existing software tools. The report, which contains more detail, is with the RAF RCO for final approval.

ANNEX B - Inventory Management and Optimisation

Holding every spare part needed when and where required will never be efficient or affordable.

There are many metrics of spares availability, but System A_0 is the most important. Optimised inventory should deliver '*Happy Systems*' not just '*Happy Shelves*'.

Required spares stocks are defined by the Range and Scale by location.

Spares provisioning requires both Initial Provisioning (IP) and Re-Provisioning (RP).

There are 2 principal spares provisioning methods: Single-Item Modelling that assesses each item in isolation and ignores its cost; and Availability-based system modelling that assesses all items simultaneously using its costed-weighted contribution to A_0 using a Marginal Analysis Technique.

Availability-based system modelling costs are typically 50% of the cost of engineering judgement and 25-33% cheaper than Single-Item Modelling.

Automated Re-Provisioning systems use Single-Item Modelling methods and erode the initial benefit from Availability-based IP. Given the potential waste, Availability-based Modelling should be used for RP through-life.

Providing spares does not deliver effective support since maintenance activity also requires other resources, such as skilled people, tools, test equipment, facilities, documentation etc. Multi-resource optimisation is necessary.

Optimised Inventory Management

Having every spare part available immediately when and where required will almost certainly be excessively costly and unaffordable. Therefore, optimising the inventory of spare parts at each location is a major objective of supportability analysis to maximise system availability for the lowest cost investment.

System Availability

While spares availability is important, holding inventory has a cost to acquire, store and manage; it may also require periodic in-storage maintenance even if it is not used. Therefore, stock levels should be justified for their contribution to system availability and not as an end in themselves. For example, because components have different failure rates, it might be more cost-effective to hold 2 items of an unreliable component, but none of a more reliable one rather than stocking one of each.

Optimised inventory should deliver **'*Happy Systems'*** not just **'*Happy Shelves*'**. Overstocked shelves may provide subjective comfort to logisticians, and a good source of income for suppliers, but are wasteful. The most common metric is A_0, which measures the operational availability of the system.

Spares Availability Metrics

Inventory optimisation ensures that the correct items are available in the correct location when needed <u>for the available budget</u>. The graph in Figure 23-1 below shows possible indicative relationships between system A_0, Fill Rate and Delay Time. Increasing investment improves the spares satisfaction fill rate which delivers more system availability and similarly reduces the average delay time.

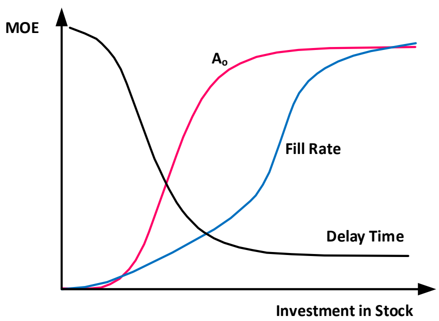


Figure 23-1: Relationship between System Availability, Fill Rate and Delay Time

There are many specific metrics of spares availability. Off-the Shelf Satisfaction Rate (OSSR) reflects the proportion of demanded items that are immediately available. Overall Satisfaction Rate (OSR) measures the proportion of items that are available, but not necessarily in the right location. OSSR and OSR are both Fill Rates which describe the confidence of having a part available when required.

Spares that are not available result in Back Orders (BO) on manufacturers and repair organisations, which implies delay. Cannibalisation is a temporary local tactical expedient to manage urgent supply shortfalls; ideally, this should be eliminated, but that would be unrealistic and excessively expensive.

To preserve system availability, the number of spares held as stock must be sufficient to cover the time taken to replenish the stock with a serviceable item. The main drivers are the failure rates, the RTRT if appropriate, and both the purchase and repair costs. Reducing repair turn-round and replenishment times will minimise the need to hold spares stock to cover the pipeline time. Holding more stock increases the probability of having a specific spare available when required. Modelling must not ignore the time to return unserviceable items for repair and assumes that infinite stock is available somewhere subject to delivery delay.

Spares Provisioning and Management

The purpose of spares provisioning and management is to make available the spares that maximise A_o for an affordable cost or that minimises the cost for a required A_o. To preserve system availability, the spares stock must be adequate to cover the time taken to replenish the stock with a serviceable item either by repair or as a new buy. The BOM is the list of all physical items that comprise a system.

- The **Range** is the list of items that are held as spare parts.
- The **Scale** is the number of items held at each location.

Not all items in the BOM should be provisioned as spares, not all the Range will be held in each location and scales of zero are valid.

Provisioning is the process of identifying the required Range and Scales of spares and ensuring that they are sustained.

- Initial Provisioning (IP)

  IP is conducted to define the initial spares scales for the initial in-service period; this is typically 2 years. Early in the life cycle, historic evidence of demand rates is often unavailable, IP is based on the best available predictions of failure modes and rates. However, these failure estimates can be erroneous, creating spares shortages or excesses which need to be resolved.

  IP for large systems is often divided into a number of Initial Provisioning Lists (IPL), of which the first provides data for the Long Lead Time Items. Equipment can be presented in IPL by sub-system or supplier, and it is normal for these to be in descending purchase lead time to enable order administration and delivery ahead of the Logistics Support Date.

  The content of IP is normally restricted to LRUs and Special-to-Type Test Equipment (STTTE) specific to the new equipment. Items that are common to Systems already in-service and normally procured through existing supply management, although those requirements need to be quantified and orders placed.

  Integration of IP data and illustrations is a key aspect of the introductory process and this data should form the data modules for the Illustrated Parts Catalogue (IPC) within the Technical Publications or Interactive Electronic Technical Publications (IETP).

  Because IP is nearly always conducted with uncertain data, initial Scales will always be wrong to some degree. Therefore, rather than commit all of the available IP cash to order the full optimum Scale, it would be prudent to preserve some budget flexibility to deal with the inevitable consequences of the different actual data. Items that will require overhaul in some years' time may not appear in early data gathering, but will need investment in due course and often have long lead time.

  Moreover, factors (such as reliability, prices and user demand) will change through-life. Therefore, optimal IP will never be sufficient, and the inventory must be actively managed through life to sustain, improve and mitigate any deterioration in spares performance.

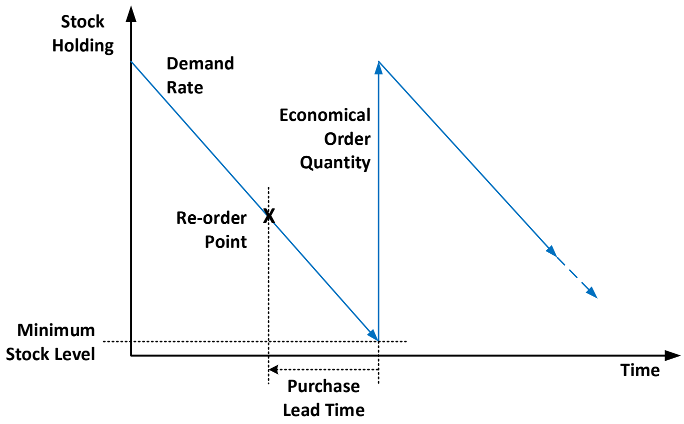
- Re-provisioning (RP)

  IP is only intended to establish sufficient stock to prime the pipeline with repairable items and, for consumables, to provide sufficient stock to allow RP processes to take effect.

  Once in-service experience generates reasonable failure data, RP uses historic consumption trends as the best indication of future need to refine the initial spares estimations to more accurately reflect the future pattern of system failure and spares demand. Whenever the system configuration is modified or upgraded, the provisioning calculations should be revisited using the best available data. Similarly, any changes to the operating pattern or support arrangements must be assessed and the impacts reflected in adjustments to the scales.

- Stock Replenishment

  Stock replenishment is a key factor in RP. The number of spares consumed in a period is defined by the rate of use of the system and item reliability. Spares must be reordered sufficiently early to allow replenishing the stock before it runs out given the procurement lead time. The number ordered will be defined by the economic order quantity. This leads to a saw-tooth pattern of stock holding as illustrated below. As there will be some random variation in demand rates, it is prudent to calculate the safety stock to retain a margin of a minimum planned stock level to cope with unusual peaks of high demand or variation in PLT.



Spares Re-order Points

Spares Provisioning Methods

There are 2 principal methods for spares modelling:

- Single-Item Modelling assesses each item in the range independently. Consequently, the cost of each item is not a factor in determining the number required and is not a discriminant on the most effective expenditure of the support budget.
- Availability-based system scaling, also known as Multi-Indenture[8] Multi-Echelon[9] (MIME), assesses all the items in the system simultaneously to identify and select those which provide the greatest contribution to overall system availability for the least cost. MIME reflects the complex environments where spares are required at multiple locations with partial or full repairs at various levels.

  Availability-based system scaling must be based on detailed knowledge of the system EBS, the operational significance of each part in the structure, the equipment attributes (such as reliability of each part in each location in the structure) and, most importantly, the costs which become a discriminant.

Single-Item Modelling (SIM)

SIM assesses each item in the range independently. Typical measures of SIM performance are OSSR and OSR which, in effect, describe the confidence of having a part available when required. These measures are also called Fill Rates. Holding more stock increases the probability of having a spare available when required.

As failures occur randomly, the mathematical probability P(n) of having a spare available when required is[10].

$$\boldsymbol{P(n) = e^{-\lambda t}\left(1 + (\lambda t) + \frac{(\lambda t)^2}{2!} + \frac{(\lambda t)^3}{3!} + \cdots + \frac{(\lambda t)^n}{n!}.e^{-\lambda t}\right)}$$

Where:

n = number of spares held
λ = failure rate
t = time to replenish stock - pipeline time.

Availability-based System Modelling

Availability-based System Modelling uses A_0 as the measure of performance. It assesses all the items in the system simultaneously to identify and select those which provide the greatest contribution to overall system

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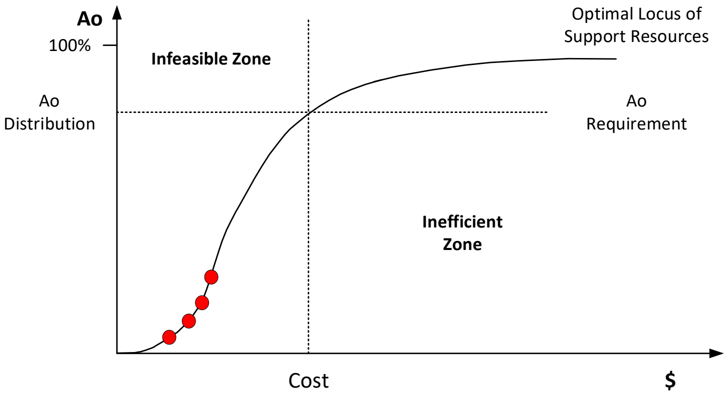
[8] Multi-Indenture reflects the system EBS such as system, sub-system, LRUs, SRUs and piece parts.

[9] Multi-Echelon reflects levels of repair such as User, and Levels 1-4. Equipment Maintenance Policies define which items are replaced and repaired if appropriate at which levels.

[10] $P(n) = e^{-\lambda t}\left(1 + (\lambda t) + \frac{(\lambda t)^2}{2!} + \frac{(\lambda t)^3}{3!} + \cdots + \frac{(\lambda t)^n}{n!}.e^{-\lambda t}\right)$
NAVAIR 00-65-502/NAVORD OD 41146 Reliability Engineering Handbook: n = number of spares held, λ = failure rate, t = time to replenish stock (pipeline time). λt is the number of fleet failures (demands) in time taken to replenish stock.

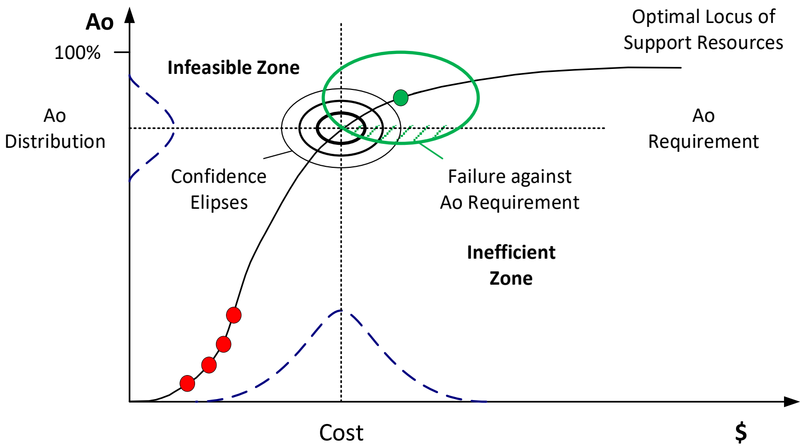
availability for the least cost. The comparative value is determined by progressively considering the individual risk of shortage for each candidate spare weighted by its cost. This can also be expressed as the number of Expected Back Orders (EBO). The initial system shortage without any spares available is 100%. By choosing to hold the spare with the largest impact on system availability, at a cost, the overall shortage or EBOs is decreased for the overall system. As the EBOs for that item is now less since some stock is available, the process is repeated to recalculate the shortage both for the overall system and for each item. This leads to a series of individual part choices that form an optimal locus of spares to achieve system availability for a specific cost until the requirement is met. This mathematical technique is called Marginal Analysis. The diagram below illustrates the technique. By definition, it is infeasible to achieve more availability than the optimal locus while any other choice is sub-optimal, inefficient and wasteful.



Marginal Analysis Locus of Optimum Part Choices

Confidence Limits

The achieved availability is based upon mean data, but failures are inherently stochastic with some statistical variation. Likewise, the cost elements may in practice be subject to some variability. This can be thought of as ellipses of confidence about the mean point as illustrated below.



Marginal Analysis Locus of Optimum Part Choices

To ensure that the probability of failing to meet the minimum requirement is within tolerable limits, the mean point must be moved up the locus to include additional items.

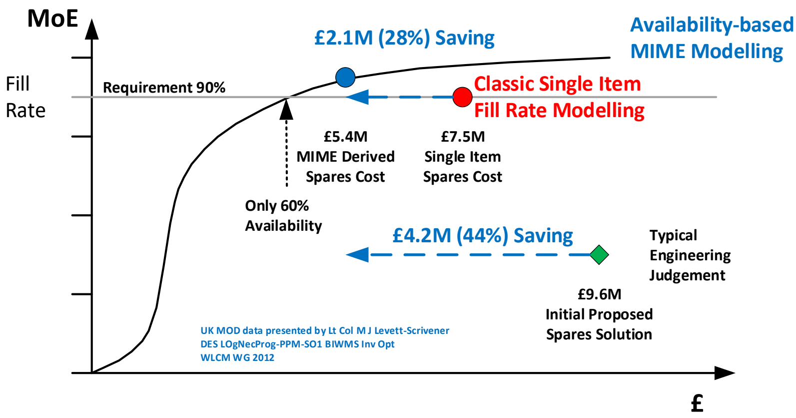
IP Approaches

There are 3 typical approaches to calculate IP stocks.

- **Engineering Judgement** based on previous experience, but this is often flawed leading to shortfalls or expensive stock holdings.
- **Single-Item Modelling** works at the item level treating each part independently. Typical measures of performance are OSSR and OSR which, in effect, describe the confidence of having a specific part available when required. These measures are also called Fill Rates. This approach can be described colloquially as ***"Happy Shelves***".
- **Availability-based System Modelling** works at system level addressing all parts simultaneously with

overall system availability the key performance metric. By choosing to hold the spare with the largest impact on system availability, at a cost, the overall risk or shortage is reduced for the overall system. MIME modelling incorporates these principles for complex environments where spares are required at multiple locations, with partial or full repairs at various levels. This approach can be described colloquially as ***"Happy Systems".***

Over many years, Engineering Judgement has proven to be least effective and most expensive. SIM is better, but for a given A_o, System-based Modelling typically produces scales that are 25-30% cheaper as illustrated below from UK MOD data; this bears out Sherbrooke's original conclusions in his book Optimal Inventory Modelling of Systems.



Relative Efficiency of IP Approaches

Consumables

Low-value consumables may be an exception to the general principle that system-based modelling should always be conducted. While the lack of consumables and piece-parts can make the system unavailable, the effort to collect modelling and the additional processing time needed to run comprehensive models may outweigh the potential savings. It may be cheaper and just as effective to adopt Kanban principles of stock management to ensure that consumables and piece parts stocks are always available even if over-stocked.

Applying cost weighting to consumables may be a useful interim measure.

Automated Re-provisioning

Once initial scales are established, stock levels are normally maintained automatically by algorithms within the various inventory management and ordering systems used for RP.

For consumables, which are typically low cost, RP is a relatively simple exercise of ordering in economic quantities sufficiently early for the remaining stock to last for the procurement lead time as illustrated above. However, current RP algorithms are fundamentally SIM approaches. If these are adopted, all the benefits of adopting system-based modelling initially for IP will be progressively eroded leading, by a reversal of the previous logic, to 25-33% more expensive and less effective solutions from SIM approaches.

A Maintenance Policy Review should be conducted regularly as suggested in Section 29 on SA, or at least before each contract re-negotiation, immediately followed by comprehensive review of in-service stock holdings using Availability-based Modelling. In many countries, this practice is not followed leading to excessive growth in unnecessary stock holdings. Industrial Primes and OEMs privately welcome the increased order flow and will not complain about the malpractice.

Because automated RP is a continuous activity without special action stock effectiveness will constantly deteriorate but will be largely unseen. Faced with other pressures, Inventory Managers do not have the capacity to conduct the necessary activity. Ideally, continuous availability-based RP should be conducted which implies an automated system.

Given the potential waste, Availability-based Modelling should be used for RP through-life.

Non-Cost Optimisation

Spares packages are normally optimised for cost since that is the typically the principal constraint when procuring spares resources.

In special circumstances, other metrics may be more appropriate. If storage space is the dominant constraint, as for example in a submarine, the spares package should be optimised using the packed volume of the spares. For air transport, weight may be the constraint and the optimisation denominator. Suitable tools must be able to use shadow currencies (such as cubic metres or kilograms) as optimisation bases.

Multi-Resource Optimisation

Inventory optimisation identifies the optimum spares at each location. However, as described in Section 10, providing spares does not deliver effective support. Maintenance activity also requires other resources such as skilled people, tools, test equipment, facilities, documentation etc.

The spares optimisation methodology uses marginal analysis to identify the next best part based on its contribution to reduce the EBO per unit of money expended. The same concept applies to the other resources, but with EBO replaced by ‘Waiting Time’. For example, maintainability is improved by reducing the waiting time for the associated mix of spares, tools and people for each task with each available at a specific cost.

Multi-resource optimisation adopts the marginal analysis technique to allocate progressively the optimum mix of resources.

Annex C - Level of Repair Analysis

Front-End Analysis (FEA) and Level of Repair Analysis (LORA) are related activities to take account of support throughout the life cycle. They must be employed to establish the expected system availability, LOR policy, spares analysis and LCC.

Front-End Analysis is conducted early in the design stages to inform equipment selection. Configuration Trade-Off Analysis allows designers to evaluate configuration options and to optimise designs for LCC.

LORA is conducted to determine the least cost feasible repair level or discard (scrap) alternative for performing maintenance actions and to drive equipment design in that direction. It is conducted to reflect maintenance policy and the capabilities of maintenance organisations with respect to the number of maintenance levels, their diagnostic capability and the skill sets and skill levels of their staff.

Depth (what) and Level of repair (where) are important independent variables which in combination define the Repair Policy for an item.

LORA is a combination of economic and non-economic factors. It is typically conducted for each item in isolation, but a holistic approach to share costs across multiple items is better and can be more cost effective.

The need for frequent equipment modifications should be included in appropriate cases in Level of Repair and Change Analysis.

Sensitivity Analysis is crucial to managing program risk and cost.

Front End Analysis (FEA)

There is a very different phasing between the expenditure of cost in a programme and the point when that cost is committed. Decisions made early in the programme embed LCC that are extremely expensive to affect later. There is a rule of thumb that what costs $1 to change in concept, costs $1000 in design, $1M in manufacture, $10Ms in modifications and $100Ms through-life. To avoid this, programmes must spend money early to reduce downstream risk and cost. FEA is essential to take account of costs throughout the life cycle. FEA must be employed to establish the expected system availability, repair policy, spares analysis and LCC. It will also enable system designers and planner to:

- Cost the best design for new equipment.
- Define the best level-of-repair strategy for the support solution.
- Understand the impact on supportability and cost of part and configuration design trade-off.
- Understand the logistics of design alternatives.

System designers will often be faced with configurations options in Trade-Off Analysis. In addition to potential impact on performance and functionality, such options can have a significant impact on the requirements for support and LCC. Part and Configuration Trade-Off Analysis allows designers to evaluate configuration options and to optimise designs for LCC.

Level of Repair Analysis (LORA)

LORA is the process of determining the most suitable maintenance level for each item based on analysis of:

- System usage, including overall fleet size.
- Availability requirement.
- LCC.
- Supportability factors, including resources required.
- The repair contract incentive mechanism and cost.
- Implications of downstream modifications and upgrades, and where those should be embodied.

When designing support systems, the first question is whether to repair or scrap a faulty part. There is a balance between repair, even though this requires facilities, manpower skill and piece parts with all their associated costs and delays, and procurement of new items which also have associated costs and delays. Depending on frequency, the economy of scale may justify repair rather than replacement with new items. It is also important to examine the potential to share repair capabilities across components. LORA is a complex, multi-indenture problem across many assemblies, sub-assemblies and components to determine the optimal provision of repair and maintenance facilities to minimise overall system LCC.

LORA should evaluate all potential repair policies for the system and its major components by quantifying the LCC of the key cost drivers. The analysis produces a decision for each item within the system identifying where each maintenance action for the item should be performed. Analysis output should be the Repair

Policy for each item, and identification of the resources required. The factors which must be considered to determine cost and availability impact of repair pipeline include:

- RTRT and Repair Costs.
- OST and RST.
- PLT.
- Stock Levels for LRUs and Piece Parts.
- Test Equipment and Facilities.
- Skills, Labour and Training.
- Technical Publications and Data.
- Packaging & Handling.
- Disposal Costs or Salvage Values.

LORA will inform choices about the optimum Depth and Level of Repair (LOR), and the optimum location. There is a very important distinction between the Depth (what repair is conducted) and the Level or Line (where repair is conducted). While there may be some correlation in practice, and some nations draw no distinction, Depth and Level are independent. Location will depend on Level or Line and is merely geographical although some of the data may vary by location.

Depths of Repair

The Depth of repair describes what repairs can be conducted on an item. There are commonly 4 Depths:

- Depth A maintenance is directly concerned with preparing the item for use and keeping it in day-to-day order.
- Depth B maintenance and repair activities are beyond those identified as Depth A. They do not normally require specialised skills and support resources.
- Depth C maintenance and repair activities are beyond those identified as Depth B. They repair items identified as faulty during Depth B and normally require more advanced skills and support resources.
- Depth D is full reconditioning and overhauling.

In addition to the Depths, additional categories are useful:

- Discard (Scrap). Where no maintenance or repair is carried out, items may be discarded as scrap. This can occur at any Depth.
- Filter Bench. Where testing is carried out to confirm a fault, but no repair is carried out, the activity is called a Filter Bench (FB). This eliminates NFF items from the repair loop.

Levels of Repair (LOR)

Traditionally, there are 4 Levels of maintenance which define the location; it is sometimes also called LOR:

- Organisational Level (O-Level, also called 1st Line) maintenance occurs at the operating unit, for example by a single maintenance squadron as part of an aircraft wing.

  O-level maintenance is typically optimised for quick turn-around to enhance operational availability. Maintenance at this level typically consists of initial diagnosis of faults on the system, immediate Removal and Replacement (R&R) to replace unserviceable LRUs with serviceable items taken from inventory stock. Repair-in-place (RIP) procedures are also used.
- Intermediate Level (I-Level, also called 2nd Line) maintenance requires facilities which do not exist within the operating unit. These are typically specialised workshops.

  I-Level maintenance deployment can vary widely and is highly dependent on the operating conditions. In minimal maintenance concepts, there may be minimal or no I-Level maintenance.

  I-Level maintenance is more specialised with more thorough and time-consuming diagnostic testing and repair usually of items removed at O-Level. Test equipment is more commonly used at I-Level and can include automated test procedures. LRUs can be repaired using Shop Replaceable Units (SRU) or piece parts from inventory stock. Minor modifications embodied by part replacement of software re-load are typically I-Level.
- Depot Level (D-Level, also called 3rd Line) maintenance requires extensive diagnostic equipment, highly specialised repair capabilities, workload capacity and possibly manufacturing capabilities which are not available at I-Level. Equipment overhauls and some major modifications are typically D-Level maintenance.

  Depots are not normally at operating locations.
- Contractor Level (C-Level, also called 4th Line) maintenance normally requires specialist equipment, skills or manufacturing capabilities only available at the OEM facilities. Equipment overhaul, reconditioning and major modifications are typically D-Level maintenance.

In addition to the Levels, an additional categorisation can be useful:

- Regionalisation can be applied to adjust maintenance and repair policies geographically. This is particularly useful where the costs of holding local stock and lengthy transportation times may justify using local facilities for filter bench or partial repair. Different maintenance policies can apply to home-based and deployed systems. Regionalisation can apply at I,D and C Levels

Repair Policies

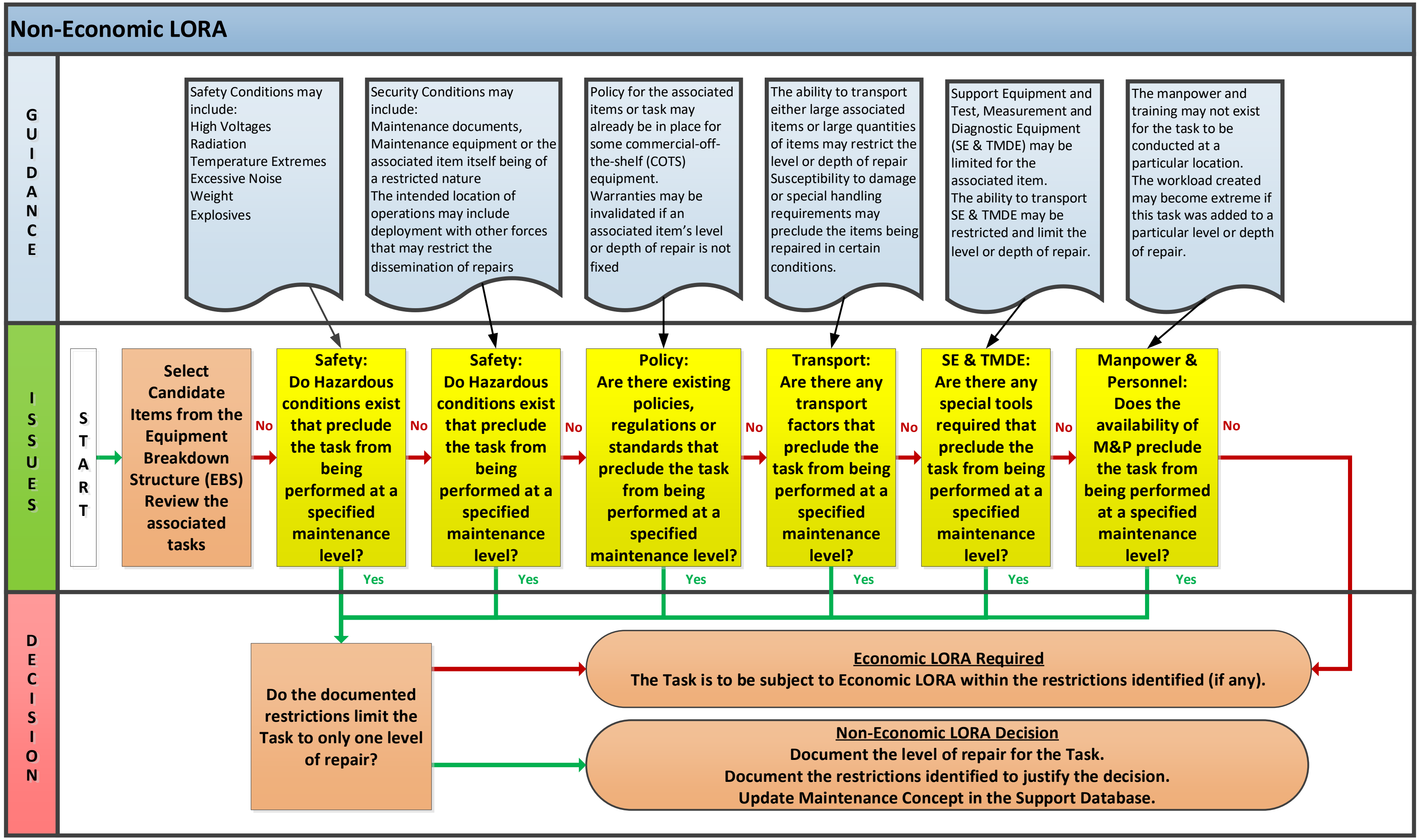
Repair Policies for an item are the combination of Depth (A,B,C,D,FB and Scrap) and Levels (1,2,3,4 including Regional) to define what and where maintenance is carried out. There are many possible options such as: 1A-2B-3C-4D; 1A-3BCD; 1A-4CD; 1A-2FB-3C-Scrap; 1A-Scrap; etc. The most effective repair policies are evaluated within LORA.

LORA Process

LORA is an economic and non-economic assessment of the costs of alternative strategies of whether to repair or scrap the item.

- Non-Economic LORA

  Non-economic LORA analyses gross concepts by conducting a non-economic analysis to influence design from a supportability standpoint. Non-economic LORA decision criteria are often a list of rules or guidelines that are used to determine if there is an overriding reason why maintenance should be performed. Some organisations have policies that any item costing less than a predetermined price level will be discarded and replaced rather than be repaired. In some cases, the maintenance policy for an item of equipment will be determined in the contract under which it was purchased.



Non-Economic LORA

- Economic LORA

  Economic LORA is conducted to determine the least cost feasible repair level or discard (scrap) alternative for performing maintenance actions and to drive equipment design in that direction. It is conducted to reflect maintenance policy and the capabilities of maintenance organisations with respect to the number of maintenance levels, their diagnostic capability and the skill sets and skill levels of their staff. It uses data from Reliability & Maintainability (R&M) analysis to include Reliability Allocation and Prediction, FMECA/Fault Tree Analysis (FTA), RCM, CBM, and the detailed procedures of the Maintenance Task Analysis (MTA) to balance Operational Availability and the cost of maintenance.

LORA Approaches

LORA is an economic and non-economic assessment of the costs of alternative strategies of whether to repair or scrap an item and at which locations / levels. For a given task, the principal variables are equipment population size; reliability or demand rate; the time taken for items to cycle through repair including shipping; repair facilities; and the various costs.

- Single Item LORA

  Long repair cycle times require more spares to populate pipelines. High demand rates caused by low equipment reliability tend to favour locating repair capabilities near to operating units, but the reduced stock cost must be offset against the need to procure and maintain repair facilities.

  Considering the repair policy for an individual equipment independently of all others means that the full cost of the repair capabilities must be justified against a single item. This is appropriate where there is no commonality with other equipment systems and their support solutions. However, it limits the population and tends to favour repair by contractors despite the cost of the pipeline and contractor repair costs. When project teams consider their systems parochially, contractor-based repair often appears to be the most economical solution.

- Multi-System or Holistic LORA

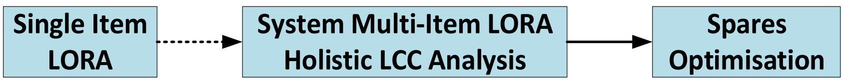
  If the cost of repair facilities is shared across many equipments, the balance of the decision often reverses to favour forward repair. Therefore, multi-system or holistic LORA is more appropriate.

  Some tools are purpose-designed to support trade-off decisions with automated sensitivity analysis but are single-system tools. While it is possible to apportion the costs of repair capabilities across multiple equipments, each of which is analysed in isolation, this approach is iterative, cumbersome, lengthy and error prone.

  In more complex cases where LORA is needed across multiple systems operating in the same theatre, a better approach to the holistic issue is to use a system-based LCC tool which can analyse the costs of various options for multiple equipments at multiple locations and at multiple equipment breakdown levels.

  Once the repair policy for each equipment is defined, it is appropriate to refine the precise ranges and scales of spares required at each location to support that policy. This must accommodate the inevitability that the scenarios, reliabilities and costs will change over time.

  The overall LORA & LCC modelling approach is shown below:



Single and Mutli-Item LORA and Spares Optimisation

- Level of Repair & Change Analysis

  Longer system in-service lives and consequent greater exposure to obsolescence have increased the need to embody modifications in-service. Some modifications require major on-platform change, but many are embodied by changes at LRU level. In other words, modifications can be embodied, as part of and using the normal repair process and facilities, but with new SRUs or piece parts.

  This is particularly appropriate for electronic and software-controlled items. In some cases, the additional loading could swing the balance from C-Level repair to I-Level activity.

  As an example, consider a small fleet with highly reliable electronic items. This implies a C-Level repair policy which, despite typically long turn-round times of perhaps 180 days, can be supported by low stock levels of perhaps only a single spare.

Where there is a high operational demand for change, the required modification rate will be high. Using the normal C-Level repair loop implies that the modification programme could take years to complete, but would consume the available spares stock – and should that be provided at pre- or post-modification state? Often additional stock must be bought to seed the modification programme which, once complete, becomes redundant. An alternative cheaper and faster solution is to conduct modifications using I-Level repair capabilities with much shorter turn-round times of perhaps only 7 days.

In some cases, where the need for frequent modifications is likely, LORA should be conducted allowing for change as LOR and Change Analysis.

Sensitivity Analysis

Designing for the support of systems can be complex and, consequently, it is important to be able to understand which factors have, or have potential, to have most impact on overall performance and LCC. Sensitivity Analysis enables system designers and planners to identify which factors have the greatest impact of the outcome, and these are not always the most obvious ones. When performing LORA, input parameters, such as fleet size, utilisation rates, deployment pattern, reliability and the frequency of scheduled or unscheduled events should be adjusted to evaluate sensitivities. Identifying these sensitivities is crucial to managing program risk and cost. Inputs, such as cost, shipping, procurement and repair and lead times should also be altered to identify the thresholds at which changes become significant. Using the SWOT technique (Strengths, Weaknesses, Opportunities and Threats) to assess the LORA model and its data is a sound method to understanding the biggest risk to the output cost, and the variables that drive that are the sensitivity candidates.